BALANCING SUSTAINABLE AGRICULTURE AND THE ENVIRONMENT THROUGH BIOECONOMY APPROACHES

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Abstract

Sustainable agriculture requires maintaining productive capacity while protecting the natural capital on which agricultural systems depend. This paper examines how bioeconomy approaches may support this balance by integrating resource utilization, environmental performance, and economic decision-making. Drawing on the literature on the circular bioeconomy, natural capital, and sustainability transitions, the paper identifies three interconnected processes. Circular agri-food value chains can create value by converting residual biomass and agro-food by-products into energy, soil amendments, and bio-based products. Accounting methods, financial instruments and economic incentives can make biodiversity, ecosystem services and natural capital relevant to investment and management decisions. Regional innovation ecosystems, in turn, provide the institutional capacity needed to adapt viable solutions and extend their application. The paper proposes an integrated framework linking value creation, value rewarding, and value scaling. Bioeconomy approaches balance agricultural production and environmental stewardship most effectively when circular resource use, credible incentives, and institutional capacity develop together.

Keywords: *circular bioeconomy; natural capital; biodiversity finance; agricultural value chains; innovation ecosystems*

INTRODUCTION

Agriculture faces many pressures beyond providing food. In addition to producing at competitive levels to protect the world's food supply, farmers must now address the effects of climate change (Babu et al., 2022). They must also continue to protect biodiversity and use natural resources more effectively (Belanger et al., 2019).

In this context, the bioeconomy provides a useful perspective for examining how agricultural systems can generate economic returns while reducing dependence on finite resources (Bugge et al., 2016). The concept extends beyond the production of goods from biological resources. It includes the valorisation of biomass, agricultural residues and food waste through processes designed to retain resources in productive use and reduce environmental pressure. Over the past decade, the bioeconomy has evolved from a relatively narrow production-oriented concept into a broader framework for rural development and sustainable transformation (European Commission 2012, 2018).

Today, it is viewed as a systemic approach that encompasses innovation processes across value chains through biotechnology and circular processes. In sustainable agriculture, significant progress has been made in identifying technologies that efficiently conserve environmental resources (Viaggi, 2018; Viaggi, 2019). Less attention has been given to the mechanisms through which these benefits become economically relevant to producers, investors, and other value-chain actors. Consequently, environmental benefits are often viewed as desirable outcomes of agricultural systems rather than as elements possessing intrinsic economic value. Therefore, balancing production sectors and environmental goals requires a better understanding of how value is distributed within agricultural systems. This encompasses not only the value of agricultural products but also the value of the ecosystem services that provide long-term system resilience (Schipfer et al., 2024).

This paper examines how bioeconomy approaches can help reconcile agricultural development with environmental sustainability. It focuses on three connected dimensions: creating value through circular agri-food systems, rewarding environmental performance through accounting and financial mechanisms, and scaling viable solutions through regional innovation ecosystems. The analysis draws on scientific literature and insights from research and innovation projects addressing circular agri-food chains, biodiversity finance, and regional innovation ecosystems.

Bioeconomy as a Systems Perspective

Early bioeconomy approaches focused on biotechnology, bio-based products, and replacing fossil inputs. The concept later expanded to include circularity, environmental limits, and social outcomes, reflecting the diversity of sectors and development pathways based on biological resources (D'Amato et al. 2017). As reflected in European Union policy initiatives, there is a clear shift toward a more holistic view. In 2012, the European Union's first Bio-Economy Strategy emphasized research, innovation, and converting renewable biological resources to produce goods and services. In the 2018 update, the emphasis shifted toward circular economies, sustainable ecosystems, biodiversity conservation, and decentralization. The bioeconomy is now seen as a framework for technological and industrial growth, integrating the economic principles of profit, societal well-being, and environmental protection (European Commission, 2012; European Commission, 2018).

From a systems-approach perspective, the bioeconomy model builds on previous work by examining how biological resources flow between sectors and the cumulative environmental impact of those actions (Geissdoerfer et al., 2017; Rodino, 2023). Additionally, it examines how organizational forms, markets, and government regulations shape where biological resources go. Therefore, the development of a bioeconomy can be viewed as an interaction among biological capital, investments in that capital, and the organizational and regulatory mechanisms that allocate it, rather than as independent technologies or industries (Viaggi, 2020). This distinction matters especially in agriculture.

Agricultural production depends directly on soils, water, climatic conditions and ecosystem functions. However agricultural practices will always modify the state of those components. Agriculture also produces outputs other than food and raw materials, such as residue biomass, ecological impacts of agriculture, jobs and spatially defined economic benefits. Because these types of production are mutually dependent, it is impossible to evaluate them independently (Giuntoli et al., 2020; Mubareka et al., 2023).

Circularity is another component of evaluating systems from a physical point of view. Residue biomass from crops, animal waste, pruning biomass, and agri-food waste can be used to produce new products through composting, nutrient recovery, bio-energy production, biochar, and other bio-based applications (Cha et al., 2016; Rodino et al., 2024; Tonini et al., 2019). While these alternatives could reduce waste loss and provide additional income for farmers, they have limitations related to competing uses for the biomass and logistical issues. Also, because maintaining soil fertility requires an amount of biomass sufficient to sustain those functions, the potential for sustainability also exists as a limiting factor (Rodino, 2024; Stegmann et al., 2020).

Therefore, rather than attempting to extract all possible biomass from farms, the goal should be to allocate available biomass appropriately. Biomass availability creates an opportunity, but economic value emerges only when feedstock supply, processing capacity, market demand, and institutional support are connected within a functional chain. Physical movement of materials explains only some of what contributes to overall performance in systems.

In addition to technical feasibility factors such as investment capacity, market demand, regulatory incentives for circular solutions, knowledge sharing across organizations, and coordination among producers, processors, academia, and decision makers also determine whether circular solutions are implemented. For example, technically feasible solutions may exist but not be used due to lack of financial backing, absence of organizational capability, or inadequate public support. Therefore, developing a bioeconomy involves changing relationships between actors and public policy configuration along with developing new technology (Viaggi, 2019). Figure 1 summarizes

these relationships, presenting the agricultural bioeconomy as a system linking natural capital, agricultural production, circular value chains, and resource regeneration.

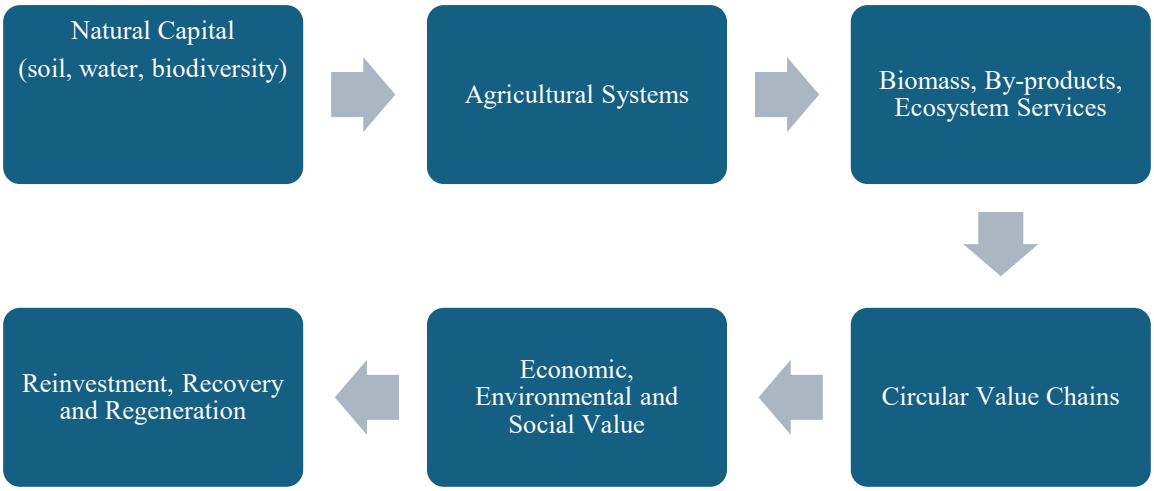


Figure 1. Bioeconomy as a system of value creation and regeneration

This multi-dimensional logic applies equally well to the EU Bioeconomy Monitoring System. When evaluating the size of the bioeconomy, economic measures such as total turnover generated by the sector, total number of employees working in the sector, and total gross domestic product created by the sector are evaluated simultaneously with environmental/societal measures of success. Because the achievement of positive results in one area can create negative consequences in another area (trade-off) or vice versa (synergy), monitoring is concerned not just with quantifying the size of the bioeconomy but with assessing the qualitative nature and sustainability of connections between actors driving that size (Mubareka et al., 2023; Giuntoli et al., 2020).

Thus, from this perspective creating a bioeconomy is essentially about organizing systems involving biological resources/economic incentives and institutional capacity so as to preserve the natural capital upon which agricultural productivity relies. That interpretation serves as the foundation for subsequent discussion of three interconnected concepts: value creation-value rewarding-value scaling.

Creating Value through Circular Agri-Food Systems

Circular bioeconomy development can offer solid contributions to the development of sustainable agriculture. One major benefit is that farmers may be able to obtain value-added products from residual materials or byproducts. Circular production systems consider various flows of materials as possible raw materials for new production processes, so long as their recovery can be performed in a way that is technically feasible, economically viable, and ecologically acceptable (Geissdoerfer et al., 2017; Stegmann et al., 2020; Schipfer et al., 2024).

Circular production is changing how agricultural residue serves as an economic resource. Reducing waste volume alone will not achieve the desired outcome. It is important for circular production to generate and maintain revenue from existing resources while reducing dependence upon external input. Additionally, circular production should create a working relationship between agriculture, food processing, the energy industry, and bio-based products.

Agricultural biomass may be converted into renewable forms of energy such as wood pellets, biofuels, heat and electricity, creating new revenue streams for farmers and providing additional diversity to local energy supplies. This allows agricultural and forestry biomass to connect primary producers with renewable energy markets, which are further enhanced by local collection and

processing when done at reasonable distances to ensure cost competitiveness (Rodino, 2024). However, energy recovery is not automatically the optimal destination for all biomass streams. Suitability of biomass resources for energy recovery depends on their qualitative and quantitative characteristics, on competing utilization options, on transportation cost, on the efficiency of conversion, on possible impacts of biomass removal on soil organic matter and nutrient balance. Prior to directing remaining fractions toward energy production, several high-value compounds or materials may be recovered. Similarly, certain crop residues may need to remain on the land.

Therefore, circular biomass management necessitates decision-making about allocation of biomass streams versus the maximum extraction of available resources (Stegmann et al., 2020). Nutrient recovery is a more direct link between circular production and sustainable agriculture development.

Manure, crop residues and agro-food processing waste can return organic matter and nutrients to agricultural soils through compost, digestate and organic fertilisers. These practices may reduce waste-management costs and dependence on mineral inputs while supporting soil structure, microbial activity and water retention. Their agronomic value nevertheless depends on nutrient composition, maturity, application rates, traceability and control of contaminants or pathogens (Ayilara et al., 2020; Hidalgo et al., 2021; Koul et al., 2022; Sayara et al., 2020).

A good example of bioeconomy products is biochar, since it allows residual biomass to be converted into value-added products, which contribute to improving soils and storing carbon (Sohi et al., 2010; Waheed et al., 2025). Biochar provides an outlet for residual biomass and can be marketed as a soil amendment. Its capacity to store carbon also makes it relevant to climate-mitigation strategies. Additionally, the production of syngas or bio-oils during pyrolysis could allow for the generation of multiple products based upon a single source of raw materials (Cha et al., 2016; Joseph et al., 2021; Rodino, 2023), demonstrating that residual streams can have many economic and ecological functions.

However, as biochar shows, value depends on designing the entire value chain appropriately, rather than relying solely on conversion technology. (Lehmann et al., 2015; Wang et al., 2019).

Valuable utilizations of biomass add to biomass valorization beyond the provision of energy and soil amendments. Residues from agro-food processing can include proteins, fibers, oils, pigments, and antioxidants that may be recoverable and useful in food, feed, cosmetic, pharmaceutical, and nutraceutical products. As such, fruit and vegetable wastes, cereal brans, oilseed cake and grape pomace should not be viewed as a homogeneous category of waste, but rather as possible sources of compounds having distinct properties and market applications (Rodino et al., 2024).

As stated above, using such products has an entirely unique economics compared to the use of large quantities of low-cost energy sources. Specialized products may generate higher returns per unit of biomass, but they also involve higher processing, quality control, and market entry requirements. They must be able to operate within established regulatory frameworks and have a market for their final products. While biomass availability could be a limitation, it would be equally limiting if the available biomass were poor quality and/or lacked sufficient usable compounds to be recovered economically. The type of biomass available and the potential to extract and recover useful chemicals from it become critical. In addition, a market must exist for the final products produced from this biomass. Such value chains connect agriculture and food processing with biotechnology, manufacturing and specialised services, each requiring different capabilities and levels of investment (Viaggi, 2018; Schipfer et al., 2024).

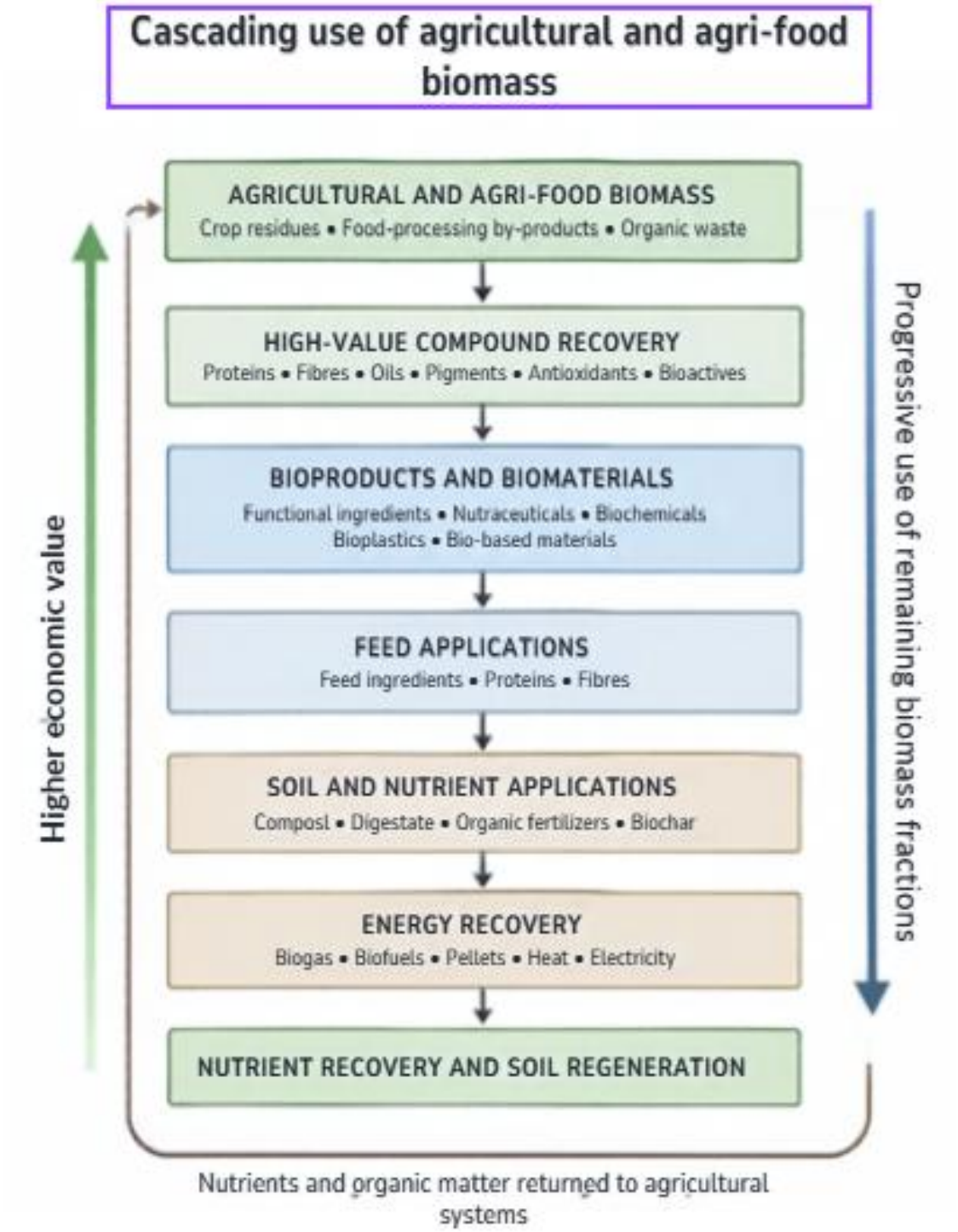


Figure 2. Cascading use of agricultural and agri-food biomass

Cascading utilizes biomass in a sequential manner based upon its composition and functional value. Energy generation is typically conducted after material or biochemical use when technologically feasible and environmentally permissible. High-value chemicals may be recovered first, followed by secondary fractions being used for animal feed, fertilizers, soil conditioners, or energy. Cascading approaches retain a higher percentage of the total economic value of the resource and reduce waste resulting from subsequent valorization processes that cannot effectively manage newly formed residual streams (Stegmann et al., 2020; Schipfer et al., 2024).

Figure 2 illustrates the main cascading pathways through which agricultural and agri-food biomass can be directed towards higher-value products, soil applications and, finally, energy recovery.

The appropriate cascade differs among feedstocks. Certain perishable residues or those contaminated with pollutants or physically located far apart may be unsuitable for specialized processing due to transportation, energy, and purification costs exceeding the value created through additional conversion. Utilization of biomass is dependent on the quality given by the physical condition of the material, seasonality, proximity to infrastructure required for processing, existing market demand, and effects on soil and ecosystem functions. Circularity should be evaluated based on the total value function preserved throughout the entire value chain, rather than only the quantity of material reused.

In addition to technological feasibility, organizational arrangement and business models constitute essential components of circular innovation. Biomass from agricultural sources is frequently produced on a seasonal basis, geographically dispersed, and variable in terms of composition. Thus, the development of collection, sorting, storage, and processing infrastructure must occur at a scale compatible with both investment costs and current market demands. Consequently, organizational structures and business models form critical elements in establishing circular innovative activities (Bugge et al., 2016; Viaggi, 2020).

Cooperative collection can aggregate biomass from smaller farms, while local processing can reduce transport costs and retain more value in rural economies. Industrial symbiosis and supply agreements can further connect residual streams with users and provide greater certainty regarding feedstock quantity, quality, and demand.

Regardless of technical circularity in a system, a system may create little incentive for primary producers if costs associated with separating, storing, or transporting biomass residuals fall disproportionately onto farmers while processors or downstream industries retain much of the increased value created. Therefore, successful collaborative arrangements rely on developing an attractive value proposition for all participants in the collaborative relationship, as well as an equitable distribution of operational risks and financial rewards (Rodino, 2024a).

Circular value creation does not require the extraction and processing of all agricultural residues. Some parts of biomass must remain on the land to preserve soil organic carbon levels, nutrient cycles, and prevent soil erosion. Other substances already contribute value within livestock production or local economies. Thus, a circular bioeconomy balances competing interests in allocating biological resources optimally rather than maximizing their commercial recovery (D'Amato et al., 2017; Rodino, 2022; Schipfer et al., 2024)

In conclusion, value creation represents the first component of the framework proposed in this paper. Circular agri-food systems offer opportunities for diversifying incomes for agricultural producers who are currently reliant on inputs purchased from outside their farm operation and maintaining biological resources in productive use. However, their ability to balance agriculture with the environment depends on how the resultant costs and benefits and environmental impacts are allocated. This relates to the second component of our framework: mechanisms that reveal environmental values and render them economically rewarding.

Rewarding Environmental Value

Agricultural systems depend on ecosystem functions and services such as soil fertility, water regulation, pollination, carbon storage, and biodiversity support. Farmers and land managers frequently bear the costs of maintaining these functions, while a substantial share of the resulting benefits accrues to society (Dasgupta, 2021). This creates a disincentive to adopt practices that will protect or improve the health of the environment.

Triple Capital Accounting considers financial, natural, and social capital together. Natural capital includes soils, water resources and biodiversity, while social capital includes livelihoods, equity and institutional relationships (Giuntoli et al., 2020; La Notte et al., 2025). Combined with Payments for Ecosystem Services, insurance products and biodiversity certificates, TCA can connect environmental performance with investment and management decisions.

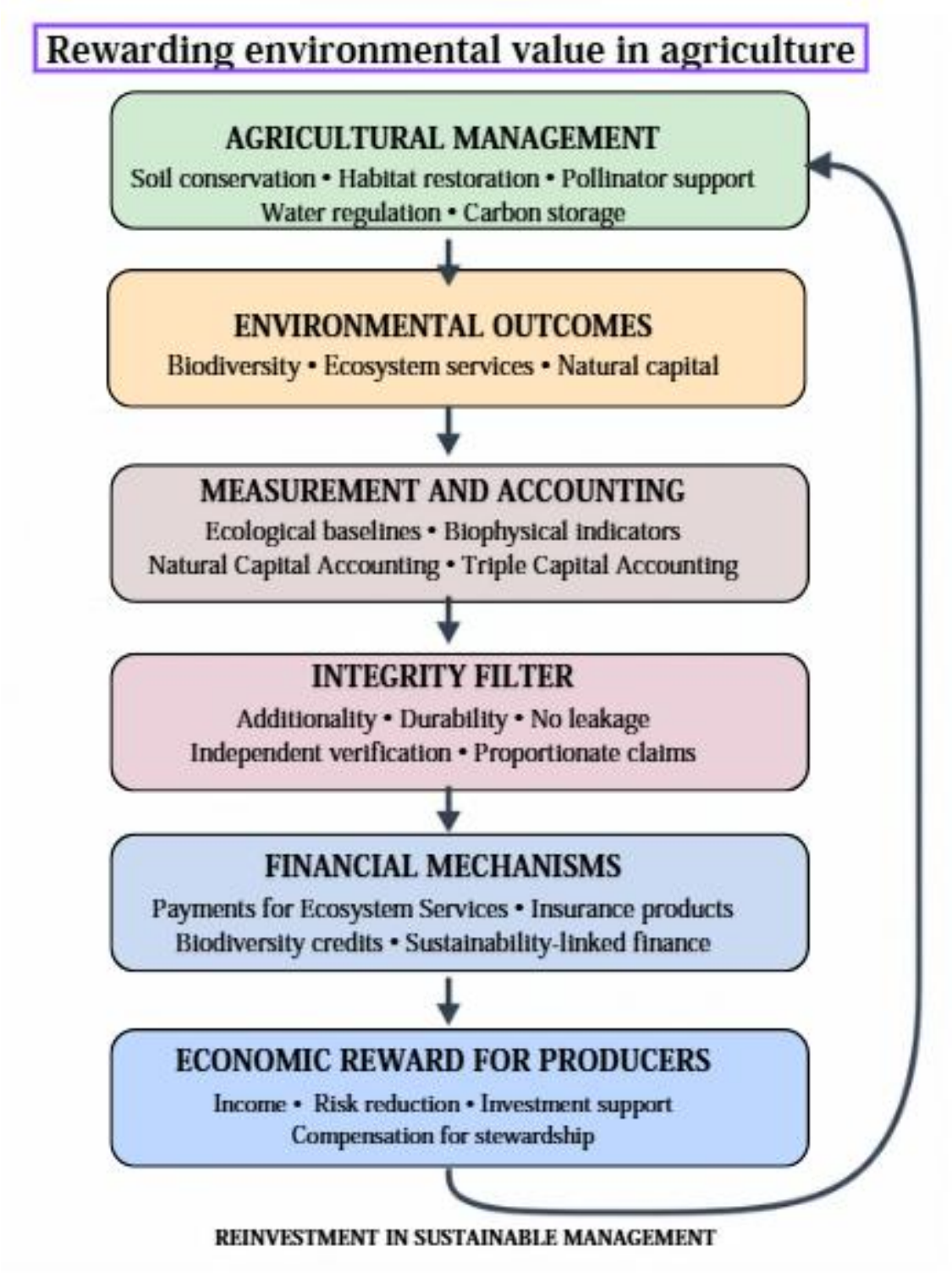


Figure 3. From environmental stewardship to economic incentives in agricultural systems

One example of a mechanism that enables financing through measurable restoration or conservation activities is biodiversity credit schemes (Kim et al., 2025). Their credibility depends on additionality, durable outcomes, appropriate ecological baselines, and reliable monitoring. Therefore, when using financial instruments, the focus needs to be on preserving the ecological context rather than treating biodiversity as an interchangeable commodity (World Economic Forum, 2025).

Financing an environmental project may demonstrate a contribution to biodiversity, but it does not automatically make an organisation, product or value chain biodiversity positive. Any public

statement should remain proportional to the measured outcome and be supported by transparent methods and independent verification (Wunder et al., 2024).

Therefore, simply establishing a financial value to nature is insufficient to establish rewards for environmental values. Rewarding environmental value requires a direct connection between ecological measurement, economic assessment, and financial incentives. Such a connection allows environmental stewardship to influence agricultural investment, land management and the distribution of returns. The pathway from environmental stewardship to economic reward is presented in Figure 3, which links ecological outcomes with measurement, verification and financial incentives.

Scaling Sustainable Solutions

Many technically viable and economically promising solutions remain confined to pilot projects or local value chains. Wider adoption depends on finance, market demand, implementation capacity, and stakeholder cooperation. Scaling therefore involves adaptation to new territorial and organizational settings rather than direct replication. Regional innovation ecosystems connect producers, research organisations, businesses, investors and public authorities. Bioeconomies at the local level or networked will be able to assist with this process by identifying competencies presently in existence and developing partnerships where possible, while also developing solutions to fit the unique production and marketplace structures of each region.

Therefore, scaling sustainable products and services requires not only technological innovations but also the establishment of new institutions. As such, the proposed framework links circular economy and green economy concepts to larger-scale transitions in production patterns, investments, and resource use.

An Integrated Framework for Balancing Agriculture and the Environment

The outcomes of these interventions depend on the wider system in which they operate. There is an interplay of biological resources, ecosystem services, markets, investments and institutions across all of these areas, and what happens in one area has either positive or negative impacts depending upon what is happening in other areas.

This paper outlines a conceptual model that represents three interconnected processes. The first process is "value creation," which refers to transforming residual biomass and agro-food by-products into energy, soil amendments, materials, and specialized bioproducts. This process creates value because it allows farmers and food processors to turn something that would otherwise be wasted into a product that adds revenue to their bottom line. The key point is that creating value is not just about maximizing the amount of biomass extracted from agricultural operations; it is also important to choose extraction methods that generate enough revenue for farmers to maintain productive land and preserve their natural capital.

The second process is "value rewarding." This process recognizes that there are significant environmental costs associated with agricultural practices. The goal of this process is to identify who should bear those costs and who receives the benefits. Tools such as natural capital accounting, payments for ecosystem services, and biodiversity-finance instruments provide mechanisms for making the environmental performance of agricultural operations relevant to both investment and management decisions. Their effectiveness depends on credible ecological baselines, measurable outcomes, and transparent verification. Without measurable ecological outcomes, these instruments risk remaining reporting or communication devices rather than drivers of change.

The third process is "value scaling". To scale up sustainable agricultural practices to achieve meaningful levels of adoption at the regional level, organizations need to adapt their strategies based on the unique local context. This includes adapting their strategies based on regional resource availability, regional market conditions, and the organizational capacities available within their region. To accomplish that, innovation ecosystems that facilitate knowledge sharing and collaborative innovation should be established. These types of ecosystems could help to ensure that effective

technologies and financial models are developed and disseminated to meet the needs of producers in various parts of the country.

Figure 4 brings together the three processes examined. The framework presents value creation, value rewarding and value scaling as mutually reinforcing components operating within an agricultural system whose productive capacity depends on natural capital.

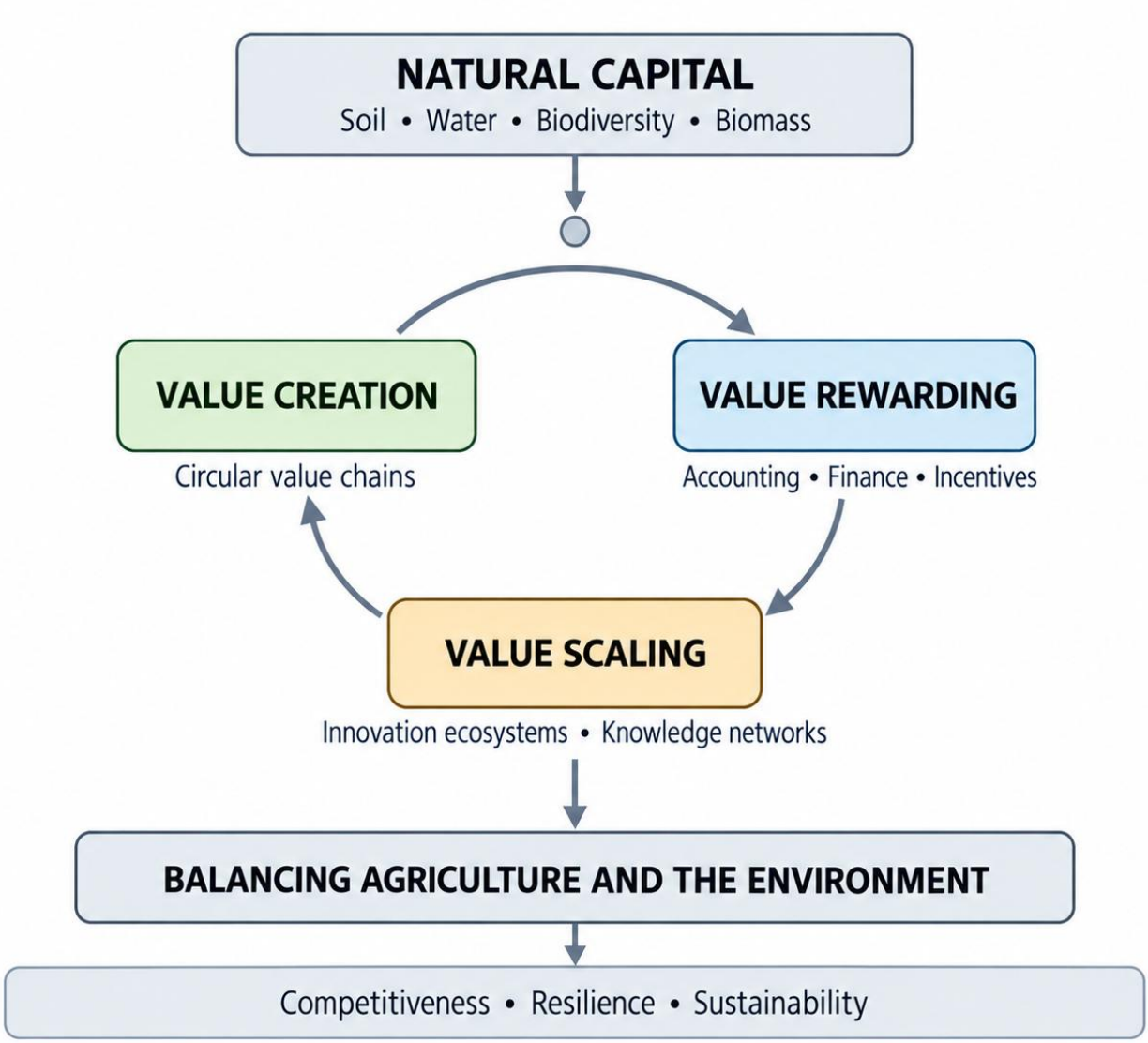


Figure 4. Integrated framework linking value creation, value rewarding and value scaling in agricultural bioeconomy systems

These processes are interactive and cumulative. A closed-loop value chain does not exist without a viable set of economic incentives and organizational structures in place. Environmental finance cannot occur unless there are credible projects with measurable outcomes. Similarly, innovation ecosystems require deployment of technologies and business models that create investment opportunities.

CONCLUSIONS

1. Sustainable agriculture and environmental protection should not be treated as competing objectives. Agricultural productivity depends on soils, water, biodiversity and functioning ecosystems. Bioeconomy approaches can strengthen the relationship between agricultural

development and environmental protection by connecting circular resource use with environmental incentives and institutional capacity.

2. The conceptual framework proposed in this paper comprises three interdependent components:

- Value creation, through circular agri-food systems that transform residual biomass and agro-food by-products into energy, soil amendments, materials and specialised bioproducts.
- Value rewarding, through financial mechanisms that make environmental performance relevant to investment and management decisions.
- Value scaling, through regional innovation ecosystems capable of adapting viable solutions to different territorial, economic and institutional conditions.

3. None of these components can support the bioeconomy transition in isolation. Circular solutions require viable business models and an appropriate distribution of costs and returns. Environmental finance depends on credible ecological evidence, while wider adoption requires organisations capable of connecting knowledge, investment, infrastructure and market demand.

4. The contribution of bioeconomy approaches extends beyond the replacement of non-renewable resources with renewable alternatives. Their broader relevance lies in reorganising the relationships among biological resources, environmental performance and economic decision-making.

5. An integrated application of these processes can support agricultural competitiveness and resilience while maintaining the natural capital on which future production depends. This provides a practical basis for balancing sustainable agriculture and environmental stewardship within the same development pathway.

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